# Chemical fingerprints of star forming regions and active galaxies

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# Highlights and Outlook

The most relevant results and conclusions obtained from the studies described throughout the thesis are presented in this final chapter. The not fully understood problems and further proposed investigation are described afterwards.

## 8.1 Remarks

Single dish observations of the $J = 3 \rightarrow 2$ transition of HNC and HCN, and the $J = 2 \rightarrow 1$ and $J = 1 \rightarrow 0$ lines of CN, are presented (Chap. 2) for the HNC-luminous Seyfert galaxies NGC 1068, NGC 1365, NGC 3079, NGC 2623, and NGC 7469. From the $J = 3 \rightarrow 2/J = 1 \rightarrow 0$ line ratios we estimate the excitation conditions of HCN and HNC in these galaxies. We conclude that in two of these galaxies (NGC 1068, NGC 3079) the HNC emission emerges from gas with densities $n(\mathrm{H_2}) \lesssim 10^5\ \mathrm{cm^{-3}}$, where the chemistry is dominated by ion-neutral reactions. The observed HCN/HNC and CN/HCN line ratios favor a PDR scenario, rather than an XDR one, which is consistent with previous indications of a starburst component in the central region of these galaxies. However, the $N(\mathrm{HNC})/N(\mathrm{HCN})$ column density ratios observed in NGC 3079 are consistent only with those found in XDR environments. However, since the starburst region is of a larger angular scale than the AGN, its effects can be contaminating the observations (through the larger beam size of the $J = 1 \rightarrow 0$ lines), leading to the favored PDR scenario found with our models.

The excitation conditions of HCN, HNC, and CN are estimated (Chap. 3) toward the nuclear region of NGC 1068, based on line intensity ratios and radiative transfer models. A first-order estimate, based on single dish observations of the $J = 1 \rightarrow 0$ lines from different telescopes (beam sizes), leads to starburst contribution factors of 0.58 and 0.56 for the CN and HCN, respectively. We find that the bulk emission of HCN, HNC, CN, and the high-$J$ $\mathrm{HCO^+}$ emerges from dense gas ($n(\mathrm{H_2}) \geq 10^5\ \mathrm{cm^{-3}}$). However, the low-$J$ $\mathrm{HCO^+}$ lines (dominating the $\mathrm{HCO^+}$ column density) trace less dense ($n(\mathrm{H_2}) < 10^5\ \mathrm{cm^{-3}}$) and colder ($T_K \leq 20$ K) gas, whereas the high-$J$ $\mathrm{HCO^+}$ emerges from warmer ($> 30$ K) gas than the other molecules. The $\mathrm{HCO^+}$ $J = 4 \rightarrow 3$ line intensity, compared to the lower transition lines and to the

HCN $J = 4 \rightarrow 3$ line, support the influence of a local XDR environment. The estimated $N(\mathrm{CN})/N(\mathrm{HCN}) \sim 1-4$ column density ratios are indicative of an XDR/AGN environment with a possible contribution of grain-surface chemistry induced by X-rays or shocks.

The first Spitzer IRS maps of the nuclear region of NGC 4945 in the fine-structure line [Ne V] at 14.32 $\mu$m, the deep silicate absorption feature at 9.7 $\mu$m, and other emission lines, are presented (Chap. 4). We estimate an extinction ($A_{\mathrm{V}}$) map based on the apparent strength of the 9.7 $\mu$m absorption feature. The peak emission of most of the extinction corrected lines coincides (within $\sim 1''$, or $\sim 18$ pc at the distance of 3.7 Mpc) with the position of the $H_2O$ maser, adopted as the location of the AGN. The [Ne V]/[Ne II] ratios obtained in all the mapped regions are lower than the ratios typically observed in AGNs. Whereas the [Ne III]/[Ne II] ratios observed along the starburst ring are consistent with the ratios expected in shocks. This is interpreted as an excess [Ne II] emission driven by the starburst ring, or by SN remnants. An extinction $A_{\mathrm{V}} \sim 5500$ mag is needed in order to obtain a typical AGN [Ne V]/[Ne II] line ratio of $\sim 0.8$ towards the $H_2O$ maser. This high extinction is consistent with the extreme column density $N_{\mathrm{H}} > 10^{24}$ cm$^{-2}$ obscuring the AGN BLR of NGC 4945, as estimated from X-ray observations.

The chemical abundances and excitation aspects of X-ray irradiation (XDR) by an AGN are studied (Chap. 5) for the molecular gas in a 3-D hydrodynamic model of an AGN torus. Line intensities are estimated using a 3-D radiative transfer code based on multi-zone escape probability techniques with fixed directions. We found an average XDR-derived temperature about $\gtrsim 1$ to $\sim 100$ times higher than the average temperature estimated in the hydrodynamical model within the inner $\pm 20$ pc radius from the torus, where the X-ray flux is $F_X \gtrsim 1.1$ erg s$^{-1}$ cm$^{-2}$. The average $H_2$ XDR-derived density, instead, follows an inverse relation with the X-ray flux, being lower (by factors up to $\sim 10^4$) than the average density of the hydrodynamical model in the inner $\pm 20$ pc around the AGN.

The CHAMP$^+$ receiver on the APEX telescope was used (Chap. 6) to map (with $7'' - 9''$ resolution, or $0.07 - 0.1$ pc at the distance of 2.2 kpc) the M17 SW star-forming region in mid-$J$ transitions of $^{12}$CO, $^{13}$CO, and in the 370 $\mu$m fine-structure line of [C I]. The warm gas was found to extend up to a distance of $\sim 2.2$ pc from the M17 SW ridge. The structure and distribution of the [C I] $^3P_2 \rightarrow {}^3P_1$ 370 $\mu$m map indicate that its emission arises from the interclump medium with densities of $\sim 10^3$ cm$^{-3}$. A non-LTE model suggests that the kinetic temperature at four selected positions cannot exceed 230 K in clumps with density of $n(\mathrm{H}_2) \sim 5 \times 10^5$ cm$^{-3}$, and that the warm ($T_k > 100$ K) and dense ($n(\mathrm{H}_2) \geq 10^4$ cm$^{-3}$) gas traced by the mid-$J$ $^{12}$CO lines represents just about 2% of the bulk of the molecular gas. The clump densities lead to clump volume-filling factors of $0.04 - 0.11$ at these positions.

The APEX/FLASH receiver was used (Chap. 7) to map the 609 $\mu$m fine-structure line of [C I] toward M17 SW. Maps of the HCN and HCO$^+$ $J = 4 \rightarrow 3$ lines are also presented. We compare the 609 $\mu$m fine-structure line of [C I] with the transition at 370 $\mu$m presented in Chap. 6. The [C I]$_{370\ \mu\mathrm{m}}$/[C I]$_{609\ \mu\mathrm{m}}$ integrated temperature ratio is $> 1$ in most of the region mapped. Assuming optically thin emission, the excitation temperature of [C I] ranges between $40$ K and $100$ K in the inner region of M17 SW. While excitation temperatures $> 100$ K are found along the eastern edge of the cloud. The column density of [C I] ranges between $\sim 4\times10^{17}$–$10^{19}$ cm$^{-2}$ in the region where the [C I] integrated temperature is larger than 50% of its peak emission. The HCO$^+$ $J = 4 \rightarrow 3$ line was found to be a factor $\sim 1-6$ brighter than HCN across the region mapped, and presents more extended emission. This unusually high HCO$^+$/HCN $J = 4 \rightarrow 3$ line ratio is argued to be an indication of irradiation by heavily obscured X-ray sources, or to be the result of a lower excitation temperature of HCN.

## 8.2 Prospects

Intense star formation, black hole accretion and the coalescence of active galactic nuclei are crucial phases in galaxy evolution. How these processes interact and drive feedback in galaxy centers, and the impact that they have on the (mostly dense, molecular) interstellar medium and star forming gas, is far from understood.

The physical properties of AGNs and the surrounding gas are often obscured at IR and optical wavelengths due to dust and large ($N_{\rm H} \sim 10^{24}$ cm$^{-2}$) absorbing columns of gas. However, (sub)-millimeter and X-ray observations do reveal these hidden processes. And high resolution observations at (sub-)millimeter wavelengths can shed light on the interaction and feedback processes between the accreting black hole and the starburst activity. Specifically, one needs a better understanding of the radiative (UV and X-ray photons), mechanical (supernova shocks and outflows) and chemical (heavy element pollution) feedback processes in nuclei of galaxies. Studies of atomic and molecular emission triggered by these processes can advance our understanding of the interaction (and feedback) between these processes in galaxy centers, and the impact that they have on the (mostly dense, molecular) interstellar medium and star-forming gas.

High spatial resolution observations of Galactic star-forming regions (e.g., M17 SW) and the Galactic center are particularly important since molecular clouds of the size of maps ($\sim 3\times3$ pc$^2$) recently reported (Chap. 7 and 6) will be resolved spatially by ALMA*, at the distance of nearby galaxies like the prototypical Seyfert NGC 1068 ($D \sim 14$ Mpc, Chap. 2 and 3) or the LIRG NGC 4945 ($D \sim 3.7$ Mpc, Chap. 4). As such, star-forming regions in our own Milky Way can serve as templates for a direct comparison with such regions in active galaxies that will become observable with ALMA in the coming years.

The (sub-)millimeter and mid-IR data I have collected for galaxies like NGC 1068, and the deeply buried AGN of NGC 4945 (Chaps. 2, 3 and 4), will provide diagnostics for unification models of Seyfert galaxies and the observable effects of viewing angle. Interferometric studies I am performing with collaborators, of the ambient conditions and kinematics of the molecular gas in the merging system Arp 299 will give insights to young starbursts, prior to the turning on period of an AGN, and pave the road for future higher resolution observations with ALMA.

* http://www.almaobservatory.org/

The higher excitation lines of CO, the bright fine-structure lines of neutral and ionized atomic carbon, nitrogen and oxygen that are (and will be) accessible with current and future instruments like APEX*/CHAMP$^+$, Herschel†/SPIRE & PACS and SOFIA‡/GREAT will allow to explore the dense, warm and hot (feedback affected) gas in the Galactic center, nearby galaxies, AGNs and starbursts. These lines will be used to probe the physical conditions within regions of active star formation in low and high metallicity environments, allowing the investigation of the role that metallicity plays in the physical structure of star-forming gas and its effect on the resulting line emission.

All these observational data will be used to constrain theoretical models based on the high resolution (pixel size of $\sim 0.25 - 20$ pc in diameter) 3-D hydrodynamical and chemical simulations of galactic nuclei and galaxies (Chap. 5). The line intensity maps of several molecular and atomic species, obtained from the 3-D radiative transfer code, will then be used to guide and interpret future extra-galactic observations that will be performed with the facilities mentioned above.

* http://www.mpifr.de/div/mm/technology_projects/apex.html

† http://sci.esa.int/science-e/www/area/index.cfm?fareaid=16

‡ http://www.sofia.usra.edu/